GUITAR FINGERING FOR MUSIC PERFORMANCE

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ABSTRACT

This paper presents a computational model of fingering for string instruments, based on a graph search approach. The implemented fingering model, which accounts for the bio-mechanical constraints of the performer's hand, is interfaced with a physical model of the classical guitar, which exploits the fingering to compute some sound synthesis parameters. The output of the system is validated against the performance of a human expert.

1. INTRODUCTION

Fingering is a cognitive process that maps each note on a music score to a fingered position on some instrument. Fingering involves several competences: *i*) musical analysis (including both structural and aesthetical issues), for the interpretation of the notes in input, *ii*) physical constraints, posed by the instrument where the notes have to be played, *iii*) bio-mechanical constraints, which characterize the possible figures of the hand. However, despite the salience of fingering in music performance, scores often lack of fingering indications, considered unnecessary (being common knowledge within a certain musical practice) or an execution choice. In the present paper we propose a general model for providing pieces with fingering, and we focus on physical and bio-mechanical constraints, leaving the contribution of musical analysis to a later work.

The fingering problem consists in determining for each note in the score, a *position* `<string,fret>` on the fingerboard and a finger of the left hand that presses it. The notion of position provides a unique identifier for the correspondence between the note and the fingerboard. A *fingered position* is the triple `<string,fret,finger>`, combining a position with one of the four available fingers. Provided that guitarists do use four fingers of the left hand (from the index to the little finger), n notes generate up to 4^n different fingerings. Since the same note can be found on up to 4 positions (Figure 1), this number might grow up to 16^n.

Works from several scientific areas approached fingering for its contributions to music performance [9]. Heijink & Meulenbroek [3] have carried out ergonomic and motor behavioral studies based on the complexity factors

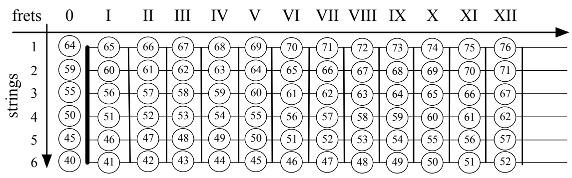

Figure 1. Outline of the notes (indicated as MIDI numbers) on a guitar fingerboard, showing that the same tone can be found on up to 4 different positions, i.e., the case of E treble (MIDI number 64), that lies at `<1,0>`, `<2,5>`, `<3,9>`, `<4,14>` (the figure displays only the first XII frets). The fret 0 indicates notes produced by plucking the string without pressing any fret.

that are implied in left hand movements of guitarists. In the modeling area, Parncutt *et al.* [5] (lately updated by Jacobs [4]), on piano playing, and Sayegh [8] on the guitar, have implemented the principle of penalizing difficulties. Cabral *et al.* model [1] also includes frequency in the repertoire.

In previous papers we have addressed two separate cases of translating the notes in the score into the actual executor's gestures, namely the case of melodies of individual notes [6], and the case of isolated chords [7]. In this paper we improve the fingering model in accounting for both cases, so that it assigns fingerings to melodies that also include chords and polyphonic passages (e.g., when a note is held, and new notes are to be played). The overall methodology transports Parncutt ergonomic approach [5] from keyboard to guitar, and shares the graph search framework with [8]. The novelties of our approach lie in the facts that we tackle melodies formed by individual notes and chords, by applying the same physical and bio-mechanical sources of difficulty to both succession and simultaneity of positions, and that we provide an experimental validation of the approach.

2. FINGERING AS GRAPH SEARCH PROBLEM

Given a music score, we build a graph that represents all the possible fingered positions sequences. For each note from left to right in the score we generate all the possible fingered positions for that note (Figure 2). This con-

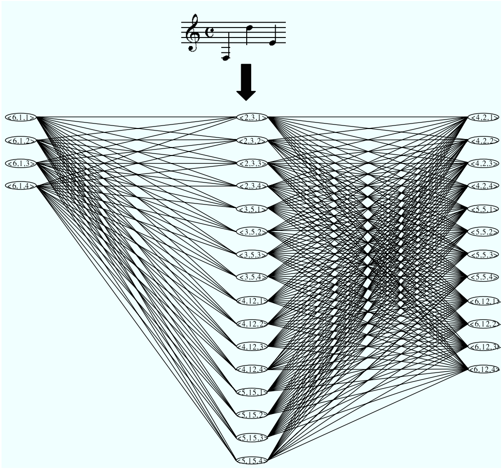

Figure 2. Graph generated for a three notes (F2-D4-E3) fragment. Each vertex represents a fingered position (e.g., `<6,1,1>`). Weights on the edges are omitted.

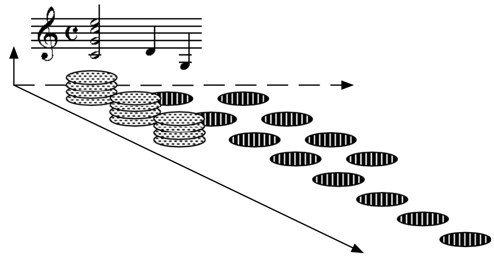

Figure 3. Chords may be considered as the third dimension of the graph: the first layer represents alternative fingerings for the same chord shape, whereas in the second and third layer, single fingered positions (for the individual notes D and G) are displayed.

struction procedure guarantees that the graph has a *layered structure*, in that the vertices can be grouped in layers, and all the edges connect vertices of adjacent layers. The number of layers is equal to the number of events, be them chords or one-note events, and any path from the leftmost layer (the first note) to the rightmost layer (the last note) represents a fingering for the score. Thus, the problem of finding a suitable fingering for a piece corresponds to the problem of finding a path in the graph.

Chords are represented as groups of vertices (collapsed into one vertex), distributed along a third dimension (Figure 3); in facts, while layers correspond to the succession of fingered notes, these groups model the simultaneity of positions in chords. Such grouped representations result from a modeling of chord fingering as a constraint satisfaction problem (CSP) [2].

Since performers pursue an overall effort-saving behavior, we assign a difficulty score (a cost) to the transitions between vertices, and seek for a path that ensures the lowest overall difficulty score. An effective traversal of the graph is then obtained by means of the *dynamic programming* technique, that can find the shortest path with linear, $O(m)$, time, where $m = |Edges|$. The piece is split into phrases, each one being fingered separately. The motivations and the salience of phrasing and musical articulation in the fingering process have been investigated by Radicioni *et al.* [6]. Since evidence was provided that hand replacements are most likely to occur at the phrase boundaries than within the phrases, we adopt a *local optimization approach*, where the model might choose a globally harder fingering, but simplifying the execution of the individual phrases.

3. ESTIMATING BIO-MECHANICAL DIFFICULTY

Here we show how weights are estimated to account for performers' bio-mechanical comfort, which kind of difficulties are considered and how they are evaluated. Weights estimating difficulties are based on the work in motor behavior by Heijink & Meulenbroek [3], on the ergonomic approach to keyboard fingering by Parncutt *et al.* [5], and on the intuitive introspection of the authors. The elements designed for the model have been quantitatively tuned on an implemented prototype.

Underpinned by [3], we assume that moving hands *horizontally* −along the fingerboard− and *vertically* −across the fingerboard− constitute two different sources of difficulty. Horizontal movements can span over a large distance, and are named *hand repositionings*, while vertical movements are considered less complex and are named *finger displacements*. The weight estimation proceeds by arranging the transitions between two positions into two classes, along the neck (henceforth *ALONG*) and across the neck (*ACROSS*) respectively. The weight (*WEIGHT*) between two fingered positions $p =$ <string$_p$, fret$_p$, finger$_p$> and $q =$ <string$_q$, fret$_q$, finger$_q$> is the linear sum of the two difficulties:

$$WEIGHT_{(p,q)} = ALONG_{(p,q)} + ACROSS_{(p,q)} \quad (1)$$

In turn, *ALONG* and *ACROSS* are computed by means of the following expressions:

$$ALONG_{(p,q)} = fret\_stretch_{(p,q)} + locality_{(p,q)} \quad (2)$$

$$ACROSS_{(p,q)} = vertical\_stretch_{(p,q)} \quad (3)$$

We assume the following value ranges for the factors mentioned here: ALONG varies between $[0, 13.25]$, with fret stretch varying from $[0.5, 5]$ and locality varying from $[0, 8.5]$ (some combinations are not possible); ACROSS as well as vertical stretch varies between $[0.25, 0.5]$. The rationale for these assignments will be clear after the description of the individual factors.

ALONG difficulties. Two factors contribute to ALONG difficulties: *Fret Stretch*, which accounts for the geometric distance between two positions on the fingerboard, and *Locality*, which accounts for transitions around some area of the fingerboard.

Fret Stretch. Given two fingered positions p and q, Fret Stretch is a measure of the difficulty due to moving horizontally. We introduce a directed distance, $deltafret =$

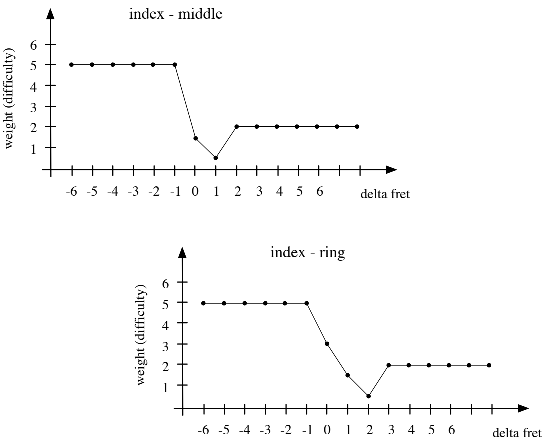

Figure 4. Example of the contribute of Fret Stretch to the WEIGH function for the finger pairs index-middle and index-ring.

$\texttt{fret}_q - \texttt{fret}_p$, which assumes negative and positive values, according whether the movement goes towards the body of the instrument or the head of the fingerboard. It is important that this distance is directed, because repositioning the hand in the direction of higher frets is easier than the opposite: so the easier direction provides positive differences, while the hardest direction provides negative differences. Fret stretch is a function of delta fret, in that it measures the difficulty for a given delta fret and finger pair. In Figure 4 we show two simplified fret stretch measures for the pairs `index-middle` and `index-ring`. Both diagrams are restricted to the significant part of the delta fret (complete diagrams would go from -17 to +17). Also, the two diagrams exhibit the same shape, by showing a predictable minimum (0.5) which is a low positive measure that is assigned when the distance between the two fingers is the *comfortable span*. The comfortable span is the distance at which two fingers can press their respective positions with a minimum effort: such transitions are thus encouraged by the assignment of a low weight. The Figure 4 (case `index-middle`) shows that we have a comfortable span between close fingers working on close frets, while the comfortable span between `index-ring` is reached when ring finger presses a position two frets higher than index, thus delta fret being 2. Instead, if the comfortable span is exceeded, a larger effort is required to perform the transition between p and q: this is the case of delta fret wider than 1 for `index-middle`, and delta fret wider than 2 for `index-ring`; in both these cases the fret stretch measure is 2. The two diagrams also show the higher difficulty for the negative directions. Finally, the two diagrams are simplified in the sense that the fret stretch also takes into account the direction over strings: when the two fingered positions are on the same fret, it expresses the preference for higher fingers to press lower strings [1], which is the relaxed formulation for a binary constraint enforced during the chords fingering [7]. This results in different measures depending on the strings involved.

Locality is defined as follows: given two positions p and q in input, $locality_{(p,q)} = \alpha \cdot (\texttt{fret}_p + \texttt{fret}_q)$, where α is a factor that depends on the technical skills of the performer and the height of the strings over the fingerboard. A suitable value we have found after preliminary test of the implemented model is $\alpha = 0.25$, so locality ranges over $[0, 8.5]$ $(8.5 = 0.25 \cdot (17 + 17))$. The locality factor accounts for the fact that playing at higher frets is itself harder than near the head of the fingerboard: going from the 1^{st} to the 17^{th} fret, strings are progressively more raised from the fingerboard, the which increases the related difficulty deriving from pressing higher fretted positions. E.g., pressing a string raised 0.2 centimeters from the fingerboard, at the 12^{th} fret, is harder than if the same string is raised 0.05 centimeters, at the 5^{th} fret: the locality factor is also motivated by the pedagogical literature which usually prescribes beginners to start playing at the first frets, because they are considered more comfortable and less tiring. Moreover, for less skilled musicians, familiarity with the fingerboard notes decreases while going away from the head of the fingerboard.

ACROSS difficulties. Across difficulties depend on only one factor, which measures the difficulty deriving from the vertical distance between fingered positions. Given two positions p and q, $deltastring = |\texttt{string}_q - \texttt{string}_p|$ is the difference in terms of intervening strings between two positions. *Vertical stretch* is the measure of the difficulty due to a given delta string for each finger pair. Also for vertical stretches we defined a *comfortable span*. Given the lesser contribution of vertical distance to the overall difficulty, we have assigned ACROSS difficulty a range in $[0.25, 0.5]$. We assign 0.25 points in the case the delta string is a comfortable span, 0.5 otherwise. We have a comfortable span between close fingers (e.g., `index-middle`) when delta string is 0 or 1; between not adjacent fingers (e.g., `index-ring`) when delta string is 0 or 3, and for the pair `index-little` when delta string is 0 or 4.

Simultaneous positions. WEIGHT accounts for the difficulty of playing simultaneous positions in a chord as well as the difficulty of playing notes in succession. For example, the fingerings for the C Major chord displayed in Figure 3 may be composed by the fingered positions in the Table below, so that the weight of each different fingering is the sum of the weight between each two positions, i.e., (C3,G3), (C3,C4), (C3,E4), (G3,C4), (G3, E4), (C4,E4).

note: C3	note: G3	note: C4	note: E4
`<5, 3,3>`	`<3, 0,0>`	`<2, 1,1>`	`<1, 0,0>`
`<6, 8,1>`	`<5,10,3>`	`<4,10,4>`	`<3, 9,2>`
`<6, 8,1>`	`<3, 0,0>`	`<4,10,3>`	`<1, 0,0>`

Respectively, the three fingerings listed (each row depicts a possible fingering for the chord displayed in Figure 3) yield the overall weights 7.5, 34.25, 17.75: each one constitutes the weight of a vertex in the graph, and is then used to compute the difficulty to reach the next graph entry, be it a chord or a single position.

[1] Recall that we start numbering fingers from index, and strings from E treble.

Recall that both the costs of locality, fret stretch and vertical stretch and the value of α were determined experimentally, on the base of several runs of the implemented model, as those leading to the average best results. The gap between the weights obtained is mainly due to the locality factor (that is, respectively 3, 27.75 and 13.5). Hence, the first fingering will be chosen as the predecessor for all the fingered positions corresponding to the next note (Figure 3), which is the note D4, and this implies that somehow the other two fingerings are pruned. If we don't want to loose the fingering solutions starting from (rooted in) the second or the third fingering, it is possible to reduce the relative strength of the locality by means of a smaller α: i.e., by setting $\alpha = 0.05$, we would yield the locality factors 0.6, 5.55 and 2.7.

4. EXPERIMENTAL VALIDATION

We have considered the written fingerings of a guitarist, bachelor in guitar performance on three pieces from the nineteenth Century didactic repertoire of the classical guitar: the *study* n.3, from the guitar method of Aguado (1843), which is a simple study on chords , the *study* Opus 60 n.7 by Carcassi, which consists of a melody with an arpeggio accompaniment, and the *Siciliana* Opus 121 n.15 by Carulli, which combines chordal and melodic passages.

We have requested the human expert to indicate the phrasing of each piece on the score, and then to mark the fingering that would have adopted in a public performance. The same pieces were given in input to the implemented fingering model, with the phrasing annotated. After the guitarist ended his task, he was requested to indicate whether in any passage the fingering computed by the model was not practicable.

Results. The fingerings computed by the model are recognized to be viable, even though two automatically fingered phrases were judged very hard to play. This demonstrates that the set of constraints is adequate at some high level. The correct fingered positions are 90.61% (respectively 95.75%, 87.69%, 88.41%). The average number of missed fingers differences (that is, correct position but wrong finger) has been 9.05% (4.25%, 12.31%, 10.59%), and the average number of wrong positions has been 2.18% (0%, 4.14% and 2.4%).

5. DISCUSSION AND CONCLUSION

On the whole, the model obtained encouraging results, even though a complete test would require several performers and a refined metric of distances.

A closer analysis of the differences reveals that the model does not still account for some 'idiomatic' gestures: over the 50% (over the three pieces) of the differences were found on scales and chords played by arpeggio. In some cases the fingerings provided by the model were not strictly worse –under the bio-mechanical aspect–, than those provided by the expert, but the expert commented that actually they would not have been even considered by any skilled musician. As earlier noted in [5], familiar fingerings may be adopted for new –similar– passages (e.g., we refer to the practice of the *transposition*, which on fretted instruments is a widespread habit). Chords and arpeggios may be part of musical patterns together with melodic fragments, and such patterns may be learned, stored and retrieved as blocks. Cognitive strategies leading to choose fingerings already known may have suggested the performer some fingerings that under the exclusive bio-mechanical aspect are not always preferable, and this could shed light on a significant part of the incorrect predictions of the model.

Future work will address such higher order issues to further improve the model's results, and the automatic analysis field, which can give fruitful contributions to the fingering problem as well.

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